AN IDEA ON DYNAMIC ALIGNMENT IN BEAM TRANSPORT LINE

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Abstract

The paper intends to apply control theory to accelerator alignment. In the paper, some major methods of control theory are introduced. The modeling of the devices in beam transport line and the project to realize optimal alignment in ion beam tuning are presented.

I INTRODUCTION

Dynamic alignment in accelerator is important. In our accelerator HIRFL (Heavy Ion Research Facility in Lanzhou) the beam tuning is done by looking at computer screens and oscillometers, and then entering the adjustable data, that is not automatic control, of course.

The control theory is some mature one, and have been widely applied in various fields. However, not many applications are reported in accelerator control. The full potential of computer control of accelerator has not, therefore, been fully exploited up to now.

This paper presents how I am preparing to employ the control theory in beam transport line which would be more simple compared with other parts of accelerator. If a satisfied result is made, I'll expand it to other parts of accelerator.

II METHOD

According to computer control theory, the feed-back control system is shown in Fig. 1, where G is the controlled plant, here is the beam transport line; D is a controller; X is a observer; Q is a identifier, All the D, X, and Q are running programs in computer.

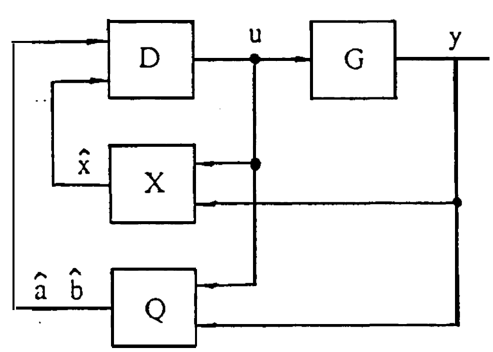

Fig.1 the Feedback Control System.

1. Controlled System G

The essential physical principle of beam transport line is that a charged particle moves in an magnetic and/or electrical field. The ion beam qualities can be adjusted by varying the currents of magnets and quadrapoles, or the voltages and frequencies of bunchers. The beam qualitiescan measured by diagnostic devices such as beam scanners, position monitors, profile monitors, phase probes, and faraday cups etc.

All these devices make up the controlled plant G in fig. 1. The input u is written data for adjusting the currents or voltages of the magnetic or electrical field. The output y is the beam qualities which are detected from diagnostic devices.

A computer control system is a discrete time system. The computer system samples measured quantities, makes calculations, and transmits adjusting data in time sequence.

A controlled plant may be represented by the following difference equations:

$$x(k+1) = A \cdot x(k) + B \cdot u(k) \tag{1a}$$

$$y(k) = C \cdot x(k) \tag{1b}$$

where k is the sampling-adjusting ordinal number for variables u, x, y, the control vector u (input) is l dimensional, the measurement vector y (output) is m dimensional, the state vector x is n dimensional, here $n >= l >= m$, A is an n x n matrix, B is an n x l matrix, C an m x n matrix.
The elements of the state vector x consist of the qualities of the ion beam everywhere, and some physical quantities reflected the operating states in the beam line, while some of them are employed for conventional mathematical treatment.

2. Controller D

Optimal control theory based on a quadratic cost function is one of the most important achievements in control theory.

In order to adjust the states of the beam line for sampling-adjusting times N from an initial vector $x(0)$ to zero vector $x(\mathrm{N})=0$, the controller D must send out a series of control vector u that depend on the sequence of the state vector x, and make the quadratic cost function J a minimum. The cost function is define by the requirement of beam tuning.

$$J = \sum_{k=0}^{N-1} [x^{'}(k) \cdot Q \cdot x(k) + u^{'}(k) \cdot R \cdot u(k)] \tag{2}$$

where Q and R are two weighting matrices, and created due to practical condition. Q is an n x n semipositive symmetric one, R is an l x l positive symmetric one. means the transposition of a matrix in this paper.

An analytical solution has been given for the finite-time fixed-end point optimal control problem in the form of the state feedback regulator. The optimal control law has the form:

$$D(k) = -R^{-1} \cdot B' \cdot (A')^{-1} \cdot [P(k) - Q] \tag{3a}$$

$$P(k) = Q + A' \cdot P(k+1) \cdot [I + B \cdot R^{-1} \cdot B' \cdot P(k+1)^{-1}] \cdot A \tag{3b}$$

where k = 0, 1, . . . N-l, P(N) = 0 could be reasonable, and then $P(N\text{-}1), \cdots P(2), P(1)$, $P(0)$ will be obtained iteratively, and so is the expression $D(k)$.

Then a series of control vector u may be offered:

$$u(k) = D(k) \cdot x(k) \tag{4}$$

This technique is popularly known as the Ricati method. There are many other methods for designing controllers. For instance, the synthesis adjusting method in classical control theory and the pole-location method in multivariable control theory are still valid and convenient.

How to get the state vector 2, and how to deal with changing parameters? That is what observer X and identifier Q function.

3. Observer X

The beam transport line is operated in the presence of strong electro magnetic fields. It is assumed to be a linear discrete-time stochastic system. The noise spectrum of the stochastic disturbances is assumed to be white noise and independent of any initial states.

Considering stochastic disturbances, the dynamic model of the controlled plant has the following form:

$$x(k+1) = A \cdot x(k) + B \cdot u(k) + H \cdot w(k) \tag{5a}$$

$$y(k) = C \cdot x(k) + v(k) \tag{5b}$$

where the definitions of x, u, y, A, B, C and k have the same meaning as those in (2); Two stochastic variables, w and v, are white noise sequences with an average of zero, and the covariance matrices of w and v are W and V, respectively.

Then, an online unbiased state estimator (i.e. observer) can be established as follows:

$$\hat{x}(k+1) = A \cdot \hat{x}(k) + B \cdot u(k) + K(k+1) \cdot [y(k+1) - C \cdot (A \cdot \hat{x}(k) + B \cdot u(k))] \tag{6a}$$

$$K(k+1) = [A \cdot G(k) \cdot A' + H \cdot W(k) \cdot H'] \cdot C' \cdot [C \cdot P(k) C' + V(k)]^{-1} \tag{6b}$$

where $\hat{x}$ is state estimation of state vector x, that $\hat{x}$ is gradually approaches $x, G(k)$ is the covariance matrix of state estimation $\hat{x}$.

The initial estimate of the unknown quantities $\hat{x}(0)$ and can be approximated by prior knowledge of the characteristics of the controlled plant — the beam line. Then the state estimate sequence $\hat{x}(k)$ can be obtained by computing (6a)(6b) successively from k = 1 to N. The larger the N, the more exact the $\hat{x}$ will be. This method is known as Kalman filter.

There are other observers available, such as: full order observer, reduced order observer and other digital filter.

4. Identifier Q

Some of the parameters of beam line will shift gradually after a long period of operation. In order to prevent this problem, the adaptive control technique should be used. Recently, a number of adaptive control algorithms i.e. identifiers, have been proposed. The dynamic coefficients (parameters) of the beam transport line could be updated in every sampling-adjusting period.

Because of somewhat sophisticated formulation, the relating expressions are not shown here. More detail for that can be found in control theory books.

III MODELING

Whatever system is considered, no quantitative analysis is possible until the various inter-relations existing among the values for system inputs, outputs, and operating states have been expressed in mathematical terms.

In general, dynamic mathematical models for a beam line describe the relationship of the beam qualities (outputs) and the adjustable data (inputs) and the states. They are expressed by differential equations or their transformations. The values of variables are small incremental changing near the steady-state operating point, usually these can be linearized.

Modeling is a basic task of automatic control engineering. The essence of good modeling is the skillful retention of the dominant phenomena while ignoring the secondary effects.

The dynamic models derived from the physical formula can not help much in modeling, I think, because it is too complicated to be done. In practical terms, the model obtained from practical experience is more reliable and useful than one derived theoretically from the physical formulas.

The first modeling can be done by some instruments or normal method. A crude model can be written down when the wave shapes of input and output are being seen on a double trace oscillometer or a set of input ant output data are detected. For example, a step function signal is inputed into a device, then observe its output, the unit transient response does adequately reflect the qualitative behavior of the device considered. The main poles and zeros of its transfer function can be estimated, so an empirical model is obtained. Or we can use a frequency response detector to obtain a frequency response model.

The further modeling work for precisely determining the system parameters will be done by identification method of control theory. Basing sequence data of inputs and outputs $[u(k), y(k)]$ recorded by a computer system, a group of prediction values $\hat{y}(k)$ could be computed. To simplify the identification algorithm for real-time application, a recursive least square parameter identification scheme is used. The cost function of it is defined as:

$$J(a,b,c) = \sum_{K=1}^{N} [y(k) - \hat{y}(k)]^2 \tag{7}$$

where a, b, c are the elements of matrices A, B, C respectively. By means of computer, a group of parameters a, b, c may be selected when the cost function J achieves a minimum, which is called a curve-fitting method. Sometimes, it is possible to simulate the inequality constraints in which the original physical quantities are restricted within the permitted range. No parameter can be reached outside of the predefined range.

Of course, it is a time consuming job to identify a complicated model.

IV PROJECT

This engineering of dynamic alignment in beam transport line is expected to be started next year.

Firstly, get familiar with the present state of our beam tuning.

Secondly, try to set up the models of the devices in the beam line, such as: a power supply of magnet, a magnet for beam transportation, then the whole plant of the beam line. Almost invariably, modeling leads to a compromise between the accuracy of representation and the treatability of mathematical form. It is wise to develop a model as simple as possible to fit its observed behavior. It is vital to remember the nature of the approximations made at every stages.

Thirdly, design the controller, observer, and identifier on the computer system. The complex program should be like that once a expected beam qualities are entered, the program automatically issues a series of control signals to force the system reach the expected state with optimal behavior during beam tuning or after being disturbed.

Fourthly, try and fail, until success. I am sure that “hill climbing” method is useful for the test job if there is no way to go. And the sampling- adjusting period should be as short as possible.

I hope we may get a satisfied result and expand to other parts of our accelerator machine HIRFL.

It is regrettable that there is an unbalance between the relatively advanced level of control theory and the relatively slow tempo of the implementation of this theory in engineering practice. I hope this paper may lead enterprising engineers to a better understanding of the control systems of accelerators and start them to improve their control system by using control theory.